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During this contract, research was performed to understand how acoustic radiation propagates in shallow channels using a full three-dimensional formulation that takes into account the finiteness of the characteristic correlation lengths of the index-of refraction fluctuations and surface height variations. The equations governing the modal coherence functions were derived by first developing difference equations over propagation distances that were large compared to the characteristic correlation lengths but small compared to the characteristic length during which there was significant energy transfer between modes. It was then shown under what conditions these equations could be reduced to partial differential equations that were valid for long-range propagation. Using a spectral formulation the equations were subsequently generalized to wide-angle scattering in the transverse direction. Differences between the two-dimensional and three-dimensional problems were found in a variety of cases. Numerical solutions were given to show how the energy is transferred between modes as the acoustic radiation propagates in the shallow channel.

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During the contract period the following topics were considered.

1) Combined volume and surface scattering in a channel, using a modal formulation.

2) Derivation and solution of the generalized coherence equation for linear sound-speed profiles and a bottom impedance condition.

3) Spatial spectral analysis of scattering in both infinite random media and channels.

4) The effect of random fluctuations on the two-frequency coherence function in a shallow channel.

5) Data analysis to determine vertical and horizontal correlation lengths of the random index-of-refraction fluctuations in a channel.

All topics were reported on in previous progress reports: (Jan. 1, 1994 - Oct. 31, 1994, Nov 1, 1994 - Dec. 31, 1994, Jan. 1, 1995 - June 30, 1995, July 1, 1995 - Dec. 31, 1995, Jan 1, 1996 - June 30, 1996). Here we shall report on the progress made in the entire contract period.

During the contract period most of the research was done by the principal investigator and a Ph.D student, Mr. Thomas Barnard. Dr. Frankenthal was supported by the contract for about one month. However, there was a considerable amount of research, closely related to the contract, that was done by Dr. Frankenthal but was not supported by the contract. We shall report on some this work here since it is very relevant and was done jointly with the principal investigator.

In order to complete his Ph.D. work Mr. Barnard has been awarded an Aasert grant. The principal investigator for this contract will be Prof. Beran but he will receive no salary under this contract.

1. Combined volume and surface scattering in a channel using a modal formulation.

A paper on this subject has been accepted for publication in the J. Acoust. Soc. of Amer. The proofs have been corrected and the paper should be published in the next few months. The abstract for the paper is:

Combined volume and surface scattering in a channel using a modal formulation. Shimshon Frankenthal and M.J. Beran (Department of Electrical Engineering, The Catholic University of America, Cardinal Station, Washington, DC 20064)

In previous work, a modal approach was used to study random volume scattering in a shallow channel [M.J. Beran and S. Frankenthal, J. Acoust. Soc. Am., 91, 3203-3211 (1992)]. Here, the way to include the effects of a rough channel surface in the formulation is shown. To include the effects of a rough surface, the modes are taken to be dependent on the range and transverse coordinates in addition to the depth coordinate. The propagation is studied in terms of the ensemble-averaged two-point coherence function and the equation governing the coherence function is derived. In order to insure energy conservation when the generalized modal field equations are simplified, the parabolic approximation is replaced by a method which includes both forward and backward propagating fields. The two-point coherence function is expressed as the sum over both self-modal and cross-modal coherence functions. The difference between the equations governing the self-modal coherence functions and the cross-modal coherence functions is considered. A numerical example which uses typical shallow water parameters is presented. Figures portray how the mode energies are transferred between the modes as the acoustical field propagates. (This work was partially supported by ONR).

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Preprints of this paper have been sent to ONR and reprints will be sent when they are available.

This paper and the previous paper quoted above form the basis for most of the other work done under this contract. The method used to derive the coherence equations has been extended

to consider shallow channels with linear sound-speed profiles and bottom impedance conditions. It is also used for the two-frequency problem and the spatial spectral approach. In all cases the solution of the basic coherence equations allow one to calculate the transfer of energy between the different modes as the acoustic radiation propagates in the channel. Summing over the modes one can calculate the acoustic intensity as a function of propagation distance and depth. In the two-frequency work the purpose is to determine the behavior of transient acoustic signals.

2. Derivation and solution of the generalized coherence equation for linear sound-speed profiles and a bottom impedance condition.

Linear profile

This work was done principally by Mr. Barnard. For the linear sound-speed profile problem the basic coherence equations are the same as for the constant sound-speed profile. The difference is that the eigenfunctions and eigenvalues are different and this means that the scattering coefficients change. For the volume scattering problem the change is in the following function

$$\sigma_{ijkm}(x'-x'', z'-z'') = \int_0^H dy'dy''k^2(y')\,k^2(y'')\,\sigma(x'-x'', z'-z'', y', y'') \quad \mathbf{(1)}$$
$$Y_i(y')\,Y_j(y')\,Y_k(y'')\,Y_m(y'')$$

where z is the mean propagation direction, y is the depth direction and x is the transverse direction. The function $k^2(y)$ represents the varying sound-speed profile and $Y_i(y)$ is the eigenfunction associated with the i^{th} eigenvalue. The correlation function of the index-of-refraction fluctuations is given by $\sigma(x'-x'', z'-z'', y', y'')$. Solving for the eigenfunctions and eigenvalues requires solving the one-dimensional equation

$$[d^2/dy^2 + k^2(y) - \beta_i^2]\,Y_i(y) = 0 \qquad (2)$$

where β_i is the eigenvalue.

Mr. Barnard has devoted a considerable amount of time in order to calculate the eigenfunctions and eigenvalues in a form suitable for use in the expression in Eq. (1). He has made use of previous work in the literature and has obtained solutions in

terms of Bessel functions of imaginary order. However, he has not yet found a usable expression for the modified Bessel function of this type and is currently working on the problem.

Bottom impedance condition

The case of a channel with a general impedance condition was introduced principally to account for the effect of dissipation due to the channel bottom. Here the eigenfunctions and eigenvalues are complex. As a result of the complex eigenvalues the basic coherence equations have a changed form. The coherence equation for the self modes $\langle\Gamma_{ii}\rangle$ for an initial plane wave is now

$$[\partial/\partial z - (Im\beta_i/|\beta_i|^2)\,\partial^2/\partial s_x^2 + S_{mm}]\langle\Gamma_{mm}\rangle + \sum_{k\neq m} S_{mk}\langle\Gamma_{kk}\rangle = 0 \tag{3}$$

Here S_{mk} are the scattering coefficients. We note the presence of a diffusion-like term (the term with a second derivative in s_x). For a rigid bottom the imaginary part of β_i is zero and hence the second term on the left-hand side does not appear.

Without the diffusion term the set of modal coherence equations reduce to a set of ordinary differential equations and may easily be solved numerically. With the diffusion term the set is a set of partial differential equations and are very difficult to solve. At present Mr. Barnard is formulating a marching algorithm to numerically solve the set of equations. We note that in the two dimensional problem (no variation in the transverse x direction) the diffusion term does not appear and the set reduces to a set of ordinary differential equations. This set will be solved numerically.

Some effort has also been made to find asymptotic solutions when the diffusion term is present. In some special circumstances a quasi-equilibrium solution exists where the transverse scattering is balanced by the dissipation. This leads to a spatial spectrum of the scattered radiation that does not change for large propagation distances.

3. Spatial spectral analysis of scattering in a random media.

In preparation for a spatial spectral analysis of the transverse direction in shallow water channel propagation a

spectral spatial analysis was developed for an infinite medium. (This work was performed in conjunction with Dr. Frankenthal and was not supported by ONR). A paper has been submitted for publication.

Based on this work a paper entitled "Propagation in random stratified waveguides - a modal spectral treatment" by S. Frankenthal and M.J. Beran was written and submitted to the J. Acoustical Soc. Amer. and is presently under review. An abstract of the paper is:

We consider the statistics of a forward propagating wave in a random, anisotropic, stratified three-dimensional waveguide, where modal analysis offers unique advantages. After extracting the vertical dependence in the usual way, we formulate the equations which govern the range evolution of the transverse spectra of the modal field coefficients (MTWS). A short range perturbation solution is used to derive the difference equations governing the long range behavior of the two lowest moments of the field-spectra. The conditions under which these difference equations can be approximated as differential equations are given. These equations are not limited by the parabolic approximation, and are amenable to numerical treatment by marching techniques. They are used here to study the effect of scattering on the spectral redistribution of the modal power, and the related problem of the coherence of plane and cylindrical waves. It is shown that, as a result of scattering in the transverse horizontal direction, the total beam power is redistributed among the modes in proportion to the modal eigenvalues, rather than uniformly, as two-dimensional propagation-models suggest.

4. The effect of random fluctuations on the two-frequency coherence function in a shallow channel.

In order to calculate the propagation of transient acoustic signals in shallow channels we have derived equations governing the two-frequency coherence function. From the two-frequency coherence function we may obtain the transient signal intensity by using Fourier transforms. A paper is in preparation in which the basic two-frequency coherence equations are derived. The method of derivation is a direct extension of the method used to derive the single frequency coherence equations. The two-frequency coherence equations have been derived in both the spatial and the spectral domains.

We are presently are performing numerical solutions of the two-frequency equations for use in the calculation of behavior of the transient signal. The calculations are somewhat difficult since we must have accurate numerical solutions for the two-

frequency coherence function when the non-dimensionalized frequency differences are small.

5. Data analysis to determine vertical and horizontal correlation lengths of the random index-of-refraction fluctuations in a channel.

In order to calculate the scattering coefficients in the equations governing the modal coherence functions it is necessary to know the form of the vertical and horizontal coherence functions of the index-of-refraction fluctuations. A survey of the literature showed that very little experimental data is available for shallow channels. Mr. Barnard thus undertook a study to determine information about these correlation functions. He did quite a bit of analysis for the vertical correlation and his work is summarized in the ASA abstract given below. He is still in the process of attempting horizontal correlation data but no significant results have yet been obtained.

The following abstract is the abstract of a presentation given by Mr. T. Barnard at the May 1995 ASA meeting:

Determination of vertical correlation lengths in a channel using SWELLEX-1 thermistor data. T.Barnard and M.J. Beran (Department of Electrical Engineering, The Catholic University of America, Cardinal Station, Washington, DC 20064)

In order to properly determine the volume scattering in a channel, it is necessary to know the characteristic vertical and horizontal correlation lengths associated with the random index-of-refraction fluctuations. The results we have obtained for characteristic vertical correlation lengths using SWELLEX-1 vertical-array thermistor data are discussed. The data has been analyzed for day-time and night-time observations. In addition, the results are dependent upon averaging times and this effect is discussed. Graphs are given for the standard deviation and normalized cross-correlations of the fluctuations, as a function of depth. (The vertical temperature data analyzed in this presentation was produced by NRL Code 7120 and NRAD Code 541 under ONR sponsorship. The data was supplied to us by B. Pasewark of NRL Code 7120. Our analysis was supported by ONR).

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A more complete outline of the talk Mr. Barnard gave at the ASA meeting will be been sent to Dr. Simmen with this final report.

Summary

During this contract, research was performed to understand how acoustic radiation propagates in shallow channels using a full three-dimensional formulation that takes into account the finiteness of the characteristic correlation lengths of the index-of refraction fluctuations and surface height variations. The equations governing the modal coherence functions were derived by first developing difference equations over propagation distances that were large compared to the characteristic correlation lengths but small compared to the characteristic length during which there was significant energy transfer between modes. It was then shown under what conditions these equations could be reduced to partial differential equations that were valid for long-range propagation. Equations were derived governing both the self modes (representing the acoustic energy) and cross modes (representing the coherence between the modes). Initially we restricted our attention to narrow angle scattering in the transverse direction but in the later paper using a spectral formulation this restriction was removed.

The three-dimensional formulation is quite different from the two-dimensional formulation in a number of cases. The cross-mode equations and the two-frequency equations contain transverse terms that do not vanish even if the initial acoustic radiation has no transverse variation and the medium is statistically homogeneous in the transverse direction. This makes the equations very difficult to solve since they cannot be reduced to a set of ordinary differential equations. The same difficulty occurs for channels with a complex bottom impedance condition. Here a transverse diffusion term appears in the three-dimensional formulation.

Numerical solutions were given in a variety of cases to show how the energy is transferred between modes as the acoustic radiation propagates in the shallow channel. In those three-dimensional cases where the problem could not be reduced to a coupled set of ordinary differential equations estimates were made of characteristic distances at which significant mode changes occurred. In the future marching techniques will be used to solve the coupled set of partial differential equations.

Based on the work accomplished in this contract a number of problems may be treated. The first would be to consider backscattering in shallow channel propagation. This could be done by extending the spectral approach and derive forward and backward equations governing the modal coherence equations. This has already been done in the infinite space case and some numerical solutions have been obtained. These equations could then be used to study scattering from a solid object in the channel. A second problem of importance would be to consider the generalized modal equations governing the fourth-order coherence functions. These

equations have already been derived by a doctoral student of the principal investigator but numerical solutions have not yet been obtained because of their complexity. The fourth-order equations allow one to calculate the intensity fluctuations in the shallow channel and thus give a measure of how the intensity fluctuates about its mean. Finally, the two-frequency formulation could be extended to treat both the backscattering case and the fourth-order coherence problem.